Design Gyration Number Determination of 100 mm-Diameter Asphalt Mixtures

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RESEARCH PAPER

Design Gyration Number Determination of 100 mm-Diameter Asphalt Mixtures

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Abstract

At present, there is no accepted standard by highway authorities on the compaction procedures of 100 mm-diameter gyratory compactor specimens. In previous studies on gyratory compaction, the method of either coring from 150 mm specimens, or preparing taller specimens than the usual 63.5 mm-long Marshall specimens, has been undertaken. However, the utilisation of 150 mm-moulds produces a significant amount of mechanical disturbance during the coring process of 100 mm-diameter specimens. The note-worthy aspect of this study is that a new standard for preparing gyratory compactor specimens with a diameter of 100 mm and a length of approximately 63.5 mm has been proposed for the first time. In this study, the design gyration number of the asphalt mixture was obtained by carrying out extensive laboratory testing on the specimens prepared, and by changing various testing parameters including the gyration number, angle of gyration, specimen height, and ram pressure. First, tests using 600 kPa ram pressure and a 1.25° gyration angle with varying gyration numbers were carried out. Then, the gyration angle was changed from 1.25° to 1.85° by 0.05° increments. Following that, a completely different pattern of loading level using 240 kPa with a 2° gyration angle was investigated. And finally, changing the gyration angle from 1.60° to 2.40° by 0.20° increments was carried out to provide a wider scope of investigation. As a result, the design gyration number for 100 mm-diameter asphalt mixtures was determined as 40 under medium traffic conditions.

Keywords Gyratory compaction · 100 mm-diameter specimens · Angle of gyration · Ram pressure · Design gyration number · Medium traffic conditions

1 Introduction

Gyratory compactors have been accepted as the backbone of laboratory compaction simulation over the last 3 decades. With the widespread acceptance of Superpave practices, gyratory compactors has become one of the most important pieces of compaction equipment in these laboratories. Roberts et al. [1], in their study, have drawn the most general picture of asphalt mixture design. There have been many important studies published to-date, by a number of researchers, about this realistic simulation effort and some very beneficial effects of the Superpave gyratory compactors can be found in a number of these publications from over last 2 decades [2–5]. It should be noted, that although these publications deal mostly with Superpave practices, it is not possible to consider Marshall compaction independently from these studies. So in the above-mentioned studies, the utilisation of either coring from 150 mm diameter specimens or the preparation of taller specimens than the usual 63.5 mm long Marshall specimens has been undertaken. The importance of this study is, here, a totally new standard of preparing 100 mm-diameter gyratory compactor specimens being explored for the first time. The vast majority of the other studies are about 150 mm specimens fabricated by Superpave gyratory compactors. A special study dealing specifically with 100 mm gyratory compactor specimens has been published in the literature that utilizes 100 mm-diameter moulds and not taking core samples out of 150 mm specimens [6]. The Superpave gyratory compactor system

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generally utilizes 150 mm diameter moulds. They have, however, also used 100 mm-diameter moulds to fabricate gyratory compactor specimens. As a result of their findings, they advised the Tennessee Department of Transportation (TDOT) that it is more efficient to use 100 mm-moulds in place of the 150 mm-moulds for the testing of asphalt. This practice is limited to asphalt mixtures with a maximum aggregate size of 25.4 mm. Some of the possible benefits of utilising 100 mm-moulds are as follows: (a) size of the sample is decreased by 400%, thus preparation time, storage space, and the moving of materials are reduced considerably; (b) laboratory testing in a conventional manner with specimens of 100 mm is made possible; and (c) maximum aggregate size of 25.4 mm or smaller makes up the bulk of the mixture composition for the surface layer of roadworks in Tennessee and other countries, including Turkey. As well as this, 150 mm-moulds frequently do not comply with AASHTO and ASTM requirements [6].

The superiority of this paper over Jackson and Czor's [6] is, in the present study, more than 400 specimens have been tested mechanically and lots of different compaction protocols have been used such as 600 kPa ram pressure and 1.25° gyration angle analyses with varying gyration number, changing gyration angle from 1.25° to 1.85° by 0.05° increments, a completely different pattern of a loading level of 240 kPa and a 2° gyration angle and changing gyration angle from 1.60° to 2.40° by 0.20° increments. With the aid of all these different compaction methods, we could be able to end up with a design gyration number of 40.

To begin this study, first, relevant literature on gyratory compactors was examined. Then, using gyratory compactors, 100 mm specimens were prepared and analysed, changing various testing parameters, and recording the results. Finally, the test results, indicating the design gyration number for reference asphalt mixtures as 40 under medium traffic conditions, were further examined in greater detail. Testing for similar and specific types of aggregate sources, bitumen, aggregate gradation and mixture proportions was conducted under laboratory conditions.

Table 1 Physical properties of the reference bitumen [8]

Property	Test value	Standard
Penetration at 25 °C (1/10 mm)	68.35	ASTM D 5-97
Penetration Index	−0.26	–
Ductility at 25 °C (mm)	> 1000	ASTM D 113-99
Viscosity at 135 °C (Pa s)	0.335	ASTM D 4402
Viscosity at 165 °C (Pa s)	0.073	ASTM D 4402
Loss on heating (%)	0.0572	ASTM D 6-80
Specific gravity at 25 °C (kg/m^3)	1028	ASTM D 70-76
Softening point (°C)	50.67	ASTM D 36-95
Flash point (°C)	312	ASTM D 92-02
Fire point (°C)	344	ASTM D 92-02

2 Experimental Studies Undertaken

2.1 Material Properties

Continuous aggregate gradation was used to establish the gradation limits for wearing course type 2 set by the acting standards of Turkey [7]. Crushed stone calcareous aggregate obtained from a local quarry was used. The filler was also obtained from the same source. For the preparation of the gyratory compactor specimens, locally sourced 50/70 penetration bitumen (PG 64-22) was used. The physical properties of the bitumen used are stated in Table 1. Technical data about the aggregates are presented in Tables 2 and 3. 2739 kg/m^3 is the apparent specific gravity of the filler.

2.2 The Procedure to Determine the Design Gyration Number for Reference Asphalt Mixtures

IPC Servopac gyratory compaction was used to fabricate 100 mm-specimens [9]. To have reliable results, more than 400 specimens were fabricated and put through all the calibration, testing, and validation phases [8]. To be able to make any conclusions, a standpoint was necessary for the control and interpretation of the obtained test results. The results obtained from the gyratory compaction tests were cross checked with earlier studies by various authors, respectively [10–18]. In these studies, the Marshall design procedure was used to prepare the asphalt specimens. The compaction technique of gyratory compactors is somewhat different from Marshall compaction. Despite this, the vast

Table 2 Physical properties of coarse aggregates [8]

Property	Test value	Standard
Bulk specific gravity (kg/m^3)	2698	ASTM C 127-04
SSD specific gravity (kg/m^3)	2703	ASTM C 127-04
Apparent specific gravity (kg/m^3)	2712	ASTM C 127-04
Water absorption (%)	0.191	ASTM C 127-04

Table 3 Physical properties of fine aggregates [8]

Property	Test value	Standard
Bulk specific gravity (kg/m^3)	2684	ASTM C 128-04
SSD specific gravity (kg/m^3)	2710	ASTM C 128-04
Apparent specific gravity (kg/m^3)	2756	ASTM C 128-04
Water absorption (%)	0.962	ASTM C 128-04

amount of data that have been previously obtained offered a very good foundation for obtaining the design gyration number of gyratory compactor specimens stemming from the similarities of the technical test results [14]. To find this design gyration number, very intense testing was carried out. The methods and practices followed throughout these studies are:

(a) Air void values should lie between 3 and 5% for 100 mm-gyratory compactor specimens [7].
(b) Previous studies were the guide in the search for the design gyration number [10–18]. Air void values obtained from the Marshall design were provided by the software embedded in the IPC Servopac gyratory compactor [9]. With the aid of this software, gyration angle, specimen height, air voids, unit weight, shear stress and ram pressure were able to be monitored online. Air void value was the main parameter that was monitored in detail.
(c) Although air void values were monitored in a very rigorous manner, tests on other variables were also carried out. For instance, gyration numbers were changed to be able to validate the physical and mechanical variances between the different gyration numbers. Also, the ram pressure and gyration angles values were further changed to arrive at more conclusions. Furthermore, the air voids, voids filled with asphalt, voids in mineral aggregate, unit weights, stability, flow and Marshall Quotient values were continuously cross checked with the previously prepared Marshall specimens' properties [10–18].

2.3 600 kPa Ram Pressure and 1.25° Gyration Angle Analyses with Varying Gyration Numbers

In previous studies, 600 kPa ram pressure, 1.25° gyration angle, a gyration speed of 30 rpm and at least 145 °C compaction temperature was used along with varying gyration numbers between 30 and 70, increasing by increments of 5 (no test results for 65 gyrations). Also, the gyration numbers were increased up to 135 but these gyration numbers, as can be expected, ended up with very low air void values and are therefore not included in this study. Table 4 depicts the average test results for gyration numbers of 30 (10 specimens), 35 (10 specimens), 40 (5 specimens), 45 (4 specimens), 50 (6 specimens), 55 (5 specimens), 60 (3 specimens) and 70 (36 specimens). These numerical values in a graphical manner are presented in Figs. 2, 3, 4, 5, 6, 7, 8 and 9.

At this point, the relevant information are given in Table 5 [7]. But the reader has to be aware of the fact that these standards are applicable only to Table 5 [7]. This table presents the criteria for surface courses that are stated in acting standards for just Marshall specimens.

When Figs. 1, 2, 3, 4, 5, 6, 7 and 8 are investigated, the following conclusions can be drawn:

The coefficient of determination for all of the parameters analysed are well above 0.95 except specimen height (which is 0.92); therefore, it can be concluded that the 100 mm-diameter specimens were prepared in a dependable manner providing a sound basis for future analyses.

Table 5 Criteria for surface courses that are described in the acting standards for Marshall specimens [7]

	Minimum	Maximum
Pulse count	75	75
Marshall stability (kg)	900	–
Air voids (%)	3	5
Voids filled with asphalt (%)	65	75
Voids in mineral aggregate (%)	14	–
Flow (mm)	2	4
Filler/bitumen ratio	–	1.5
Bitumen (by weight, %)	4.0	7.0

Table 4 The average physical and mechanical test values of gyratory compactor specimens resulting from 600 kPa ram pressure and 1.25° gyration angle analyses (Superpave practice) with varying gyration numbers

Gyration number	Unit weight (kg/m^3)	Voids in mineral aggregate (%)	Voids filled with asphalt (%)	Air voids (%)	Stability (kg)	Flow (mm)	Marshall quotient (kg/mm)	Specimen height (mm)
30	2441	15.111	74.854	3.790	1164.585	4.401	266.318	61.93
35	2448	14.863	76.326	3.509	1265.329	4.290	295.279	61.61
40	2451	14.763	76.936	3.395	1261.565	4.059	311.174	61.32
45	2459	14.487	78.657	3.082	1327.232	3.992	333.153	61.34
50	2470	14.109	81.112	2.654	1351.816	3.840	352.520	60.96
55	2468	14.172	80.704	2.725	1373.031	3.936	351.091	61.01
60	2481	13.723	83.755	2.217	1498.258	3.974	378.981	60.18
70	2489	13.462	85.655	1.921	1577.621	4.239	372.725	60.12

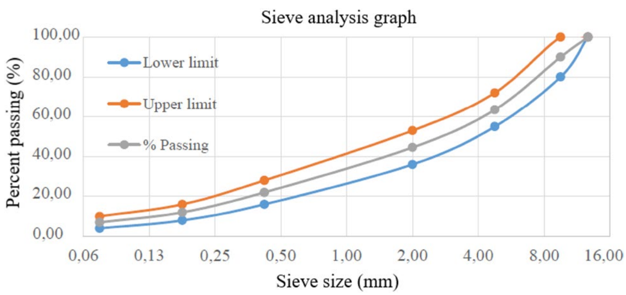

Fig. 1 Type 2 wearing course gradation [7]

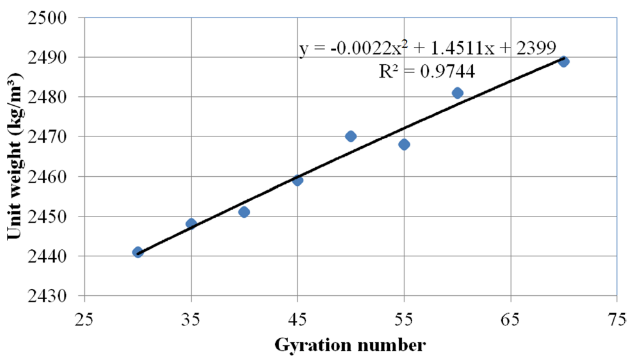

Fig. 2 Unit weight versus gyration number according to Superpave practice

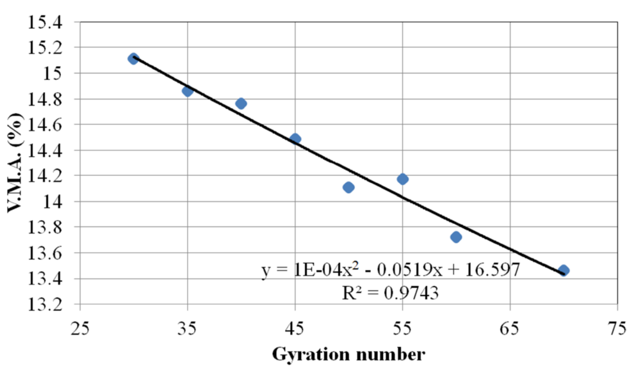

Fig. 3 Voids in mineral aggregate versus gyration number according to Superpave practice

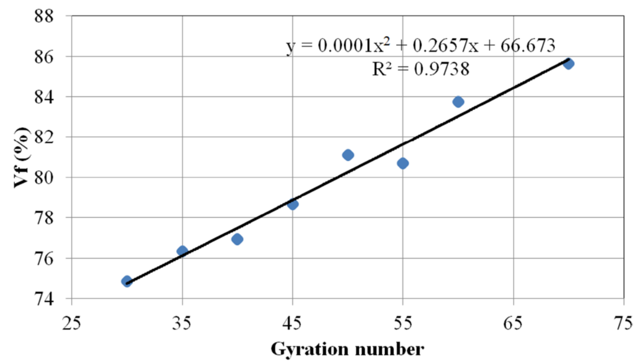

Fig. 4 Voids filled with asphalt versus gyration number according to Superpave practice

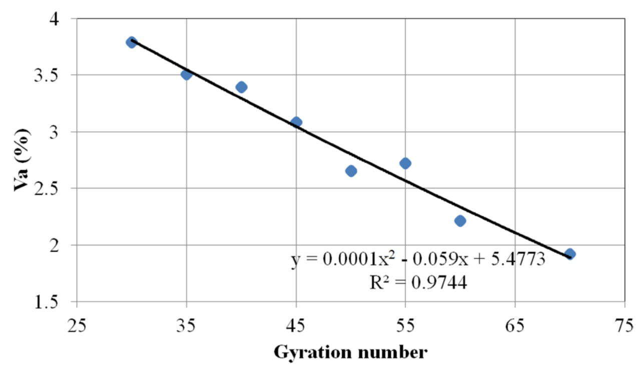

Fig. 5 Air voids versus gyration number according to Superpave practice

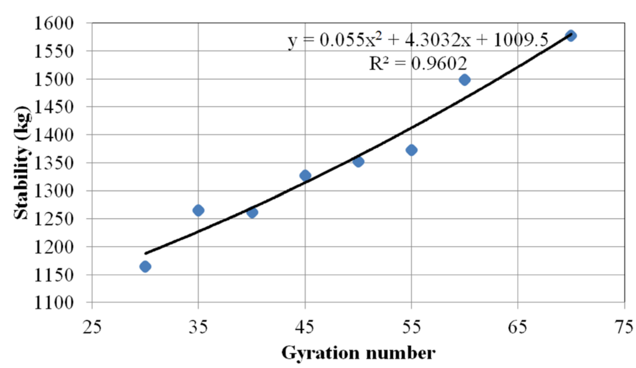

Fig. 6 Stability versus gyration number according to Superpave practice

The stability values are well above 900 kg (see Fig. 6). Therefore, there should be no problem with the maximum load the specimen could carry before failure.

At gyration numbers below 40 as highlighted in Fig. 5, the air void values are between 3.395 and 3.790%. The standards dictate that the air void values should be between 3 and 5% for an acceptable surface course mixture [7]. The obtained air void values fall well within the limits of the acting standards.

The values of voids filled with asphalt should be between 65 and 75% according to the acting standards. At 40 gyrations, (see Fig. 4) voids filled with asphalt had a value of 76.396% which is above the limit. This is a fairly predictable difference when the very different compaction pattern in gyratory compactors is considered.

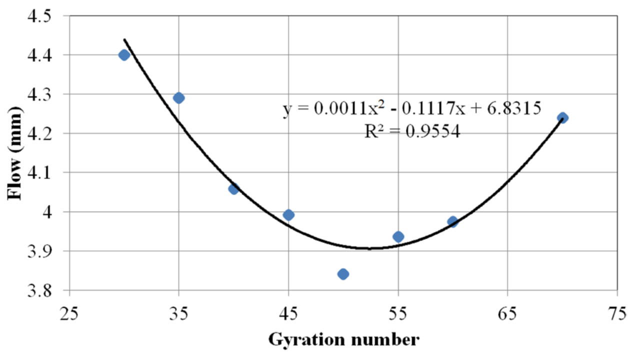

Fig. 7 Flow versus gyration number according to Superpave practice

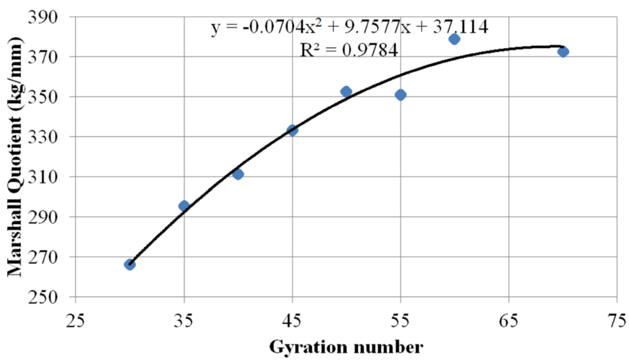

Fig. 8 Marshall quotient versus gyration number according to Superpave practice

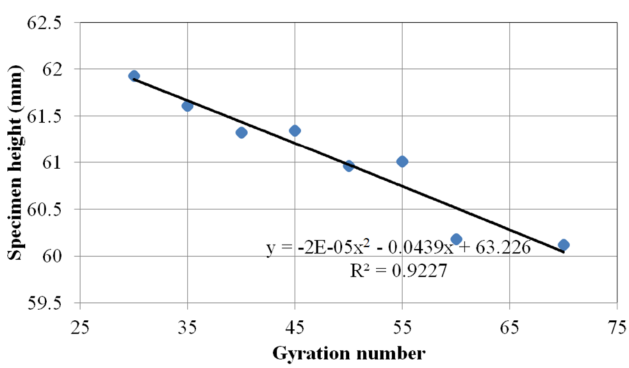

Fig. 9 Specimen height versus gyration number according to Superpave practice

The voids in mineral aggregate values are well above 14% for the gyration number values less than 40, so the limits of the standards are respected (see Fig. 3).

According to the General Directorate of Highways, the flow values should lie between 2 and 4 mm for Marshall specimens, but as the gyratory compaction technique is completely different from the previous one, the value of 4.059 mm is explicable and acceptable for 40 gyrations.

To be able to arrive at more solid conclusions, and because of the nature of gyratory compaction, further specimens with 61.5 mm height were prepared and mechanically tested [8]. The specimen heights were measured by gyratory compactor software and a vernier to increase the results reliability. Figure 9 shows the correspondence of 61.5 mm height to a gyration number of 40 being analogous with the previous results. Basically average of 6 Marshall specimens' physical and mechanical properties have been stated in Table 6. 36 more 100 mm-diameter specimens were prepared and mechanically tested to ensure the design gyration number (Table 7).

When Tables 7, 8 and 9 are analysed, it can be seen that a gyration number of 40 can be accepted as the design gyration number for 100 mm-diameter gyratory compactor specimens. The difference in flow, and therefore Marshall Quotient values, is self-explanatory as gyratory compaction is a totally different and much better method of simulating actual compaction processes on site. So, it can be concluded that flow values, by themselves, do not give a realistic or completely accurate prediction of deformation of the specimen before failure.

2.4 Changing Gyration Angle from 1.25° to 1.85° by 0.05° Increments

With 40 determined as the most likely design gyration number, a more detailed analysis was able to be carried out. (600 kPa ram pressure, 1.25° gyration angle, a gyration speed of 30 rpm and at least 145 °C of compaction temperature was used). The angle of gyration values were changed and 78 more 100 mm-diameter specimens were prepared and tested (see Table 9; Figs. 10, 11, 12, 13, 14, 15, 16 and 17 for results of these tests).

As can be seen from Table 9 and Figs. 10, 11, 12, 13, 14, 15, 16 and 17, when the gyration angle increased, as expected, the 100 mm gyratory compactor specimens became more densely compacted, causing a decrease in the air voids and specimen heights. At the same time, the values of unit weights, voids filled with asphalt, and stability values increased. Again, it is not possible to be precise about the flow and Marshall Quotient values which is evident in Figs. 14 and 15. This series of experiments provides a sound basis for the effects of changing the parameter of the angle of gyration. To further check whether changing the gyration angle to values other than 1.25° makes any significant difference, one-way anova analyses were carried out. When the averages of the test results were compared, no changes were seen between 1.25° and the other angles test results. These statistics show the significance of 1.25° as the standard gyration angle value in the gyratory compaction technique. However, there are statistically significant differences between

Table 6 Physical and mechanical properties of the specimens prepared with the Marshall compactor

Unit weight (kg/m^3)	Voids in mineral aggregate (%)	Voids filled with asphalt (%)	Air voids (%)	Stability (kg)	Flow (mm)	Marshall quotient (kg/mm)	Blows
2463	14.979	76.614	3.512	1316.0	3.261	403.557	50
2464	14.956	76.756	3.485	1279.08	2.875	444.897	50
2470	14.725	78.166	3.224	1353.18	3.870	349.659	50
2463	14.974	76.643	3.506	1325.82	3.807	348.258	50
2457	15.182	75.408	3.742	1333.80	3.560	374.663	50
2471	14.695	78.355	3.189	1158.25	3.403	340.361	50
2465	**14.919**	**76.990**	**3.443**	**1294.355**	**3.463**	**376.889**	**50**

some of the other two by two comparisons, which could be a topic for further research.

2.5 A Completely Different Pattern of a Loading Level of 240 kPa and a 2° Gyration Angle

According to Australian research, there is an important study that deals with a completely different loading level and gyration angle of the gyratory compactor to prepare specimens that resemble Marshall specimens [19]. To better investigate the subject, a new series of 24 × 100 mm-diameter gyratory compactor specimens were prepared and tested (with a gyration speed of 30 rpm and at least 145 °C compaction temperature). The results can be seen in Table 10 and Figs. 18, 19, 20, 21, 22, 23, 24 and 25.

As can be seen from Table 10 and Figs. 18, 19, 20, 21, 22, 23, 24 and 25, when the gyration number increased, as can be expected, the 100 mm gyratory compactor specimens became more densely compacted. As the level of applied stress is much lower than 600 kPa, it is evident that the number of gyrations will be higher to achieve a similar degree of compaction. See Table 11 for explanation of this phenomenon.

As can be seen in Table 11, 50 gyrations of 240 kPa–2° pattern (with a gyration speed of 30 rpm and at least 145 °C of compaction temperature) produces similar specimens to the 600 kPa–1.25° pattern. The amount of compactive force is 25% higher in the low level of stress application and produces very similar specimens. Unit weight values of the two patterns are approximately the same. Voids in mineral aggregate, voids filled with asphalt and air voids values are again, very similar to each other. So, it is clearly evident that physically, the two sets of specimens have approximately the same quantities. Marshall stability values also correlate in the two different testing protocols in an acceptable manner, but flow values do not. There is approximately a 25% increase in the 240 kPa–2° pattern which deserves attention. Therefore, it can be concluded from the data, that when the amount of compactive force increases, the flow values decrease with the gyration number.

2.6 Changing Gyration Angle from 1.60° to 2.40° by 0.20° Increments

At this point, to carry out a more detailed analysis, the angle of gyration values was changed, and 12 more 100 mm-diameter specimens were prepared and tested to further investigate the subject (gyration speed of 30 rpm and at least 145 °C of compaction temperature). The averages of three specimens for each gyration angle amount (4 specimens for 2.00° gyration angle) can be seen in Table 12 and Figs. 26, 27, 28, 29, 30, 31, 32 and 33.

When Figs. 26, 27, 28, 29, 30, 31, 32 and 33 are examined, it can be seen that when the gyration angle increases in the same gyration number pattern, the 100 mm gyratory compactor specimens become more densely compacted causing a decrease in the air voids and specimen heights. On contrary, the values of unit weight, voids filled with asphalt, and stability values increase. Again, as in the previous discussions, it is not possible to come to any solid conclusions about the flow and Marshall Quotient values, which can be clearly seen in Figs. 31 and 32. This series of experiments provides a sound basis for the effect of changing the parameter of the angle of gyration which, in fact, is responsible for the further compaction.

3 Conclusions and Further Recommendations

As a result of the above investigation, a new standard of a design gyration number of 40 has been proposed for the first time, for similar and specific types of aggregate sources, bitumen, aggregate gradation, mixture proportioning, and laboratory conditions. The testing parameters for this design

Table 7 Physical and mechanical properties of the specimens prepared with a gyratory compactor (gyratory compactor specimens were prepared by utilising 61.5 mm as the specimen height)

Unit weight (kg/m^3)	Voids in mineral aggregate (%)	Voids filled with asphalt (%)	Air voids (%)	Stability (kg)	Flow (mm)	Marshall quotient (kg/mm)	Gyration number
2441	15.126	74.750	3.807	1232.403	4.303	286.405	33
2451	14.782	76.804	3.416	1294.680	4.256	304.021	39
2455	14.631	77.734	3.245	1407.087	4.294	327.687	45
2453	14.701	77.297	3.325	1180.906	4.160	283.872	37
2449	14.860	76.326	3.505	1180.832	3.759	314.135	39
2453	14.702	77.289	3.326	1328.072	4.152	319.863	42
2456	14.595	77.957	3.204	1302.406	4.153	313.606	43
2449	14.836	76.476	3.477	1302.406	4.364	298.443	38
2464	14.337	79.597	2.913	1363.859	4.297	317.405	54
2457	14.583	78.034	3.191	1315.465	4.379	300.403	41
2458	14.548	78.248	3.152	1354.746	4.193	323.097	49
2446	14.935	75.878	3.590	1298.931	4.532	286.613	39
2442	15.079	75.028	3.753	1216.627	4.194	290.088	39
2453	14.717	77.202	3.342	1252.498	4.353	287.732	39
2462	14.402	79.182	2,985	1363.514	4.176	326.512	44
2455	14.640	77.676	3.256	1299.773	4.166	311.995	43
2449	14.849	76.396	3.492	1274.953	4.394	290.158	35
2459	14.515	78.460	3.114	1199.378	4.403	272.400	38
2454	14.686	77.387	3.308	1123.231	4.043	277.821	37
2465	14.302	79.823	2.873	1269.794	4.583	277.066	44
2451	14.765	76.784	3.420	1232.571	4.390	280.768	36
2462	14.410	79.127	2.995	1194.706	4.086	292.390	42
2453	14.720	77.180	3.346	1191.851	3.923	303.811	40
2451	14.789	76.761	3.424	1194.355	4.330	275.833	36
2455	14.648	77.625	3.265	1248.748	4.376	285.363	35
2456	14.588	78.003	3.196	1225.581	4.022	304.719	34
2467	14.222	80.351	2.782	1286.787	4.145	310.443	42
2461	14.428	79.010	3.016	1220.348	4.121	296.129	38
2466	14.259	80.110	2.823	1255.977	3.887	323.123	38
2462	14.378	79.336	2.958	1259.547	3.961	317.987	41
2461	14.435	78.966	3.024	1294.046	4.128	313.480	37
2451	14.776	76.836	3.410	1228.036	4.175	294.140	35
2462	14.404	79.167	2.988	1302.852	3.893	334.665	41
2462	14.403	79.171	2.987	1254.648	4.163	301.381	36
2457	14.570	78.110	3.177	1185.614	4.363	278.117	36
2466	14.250	80.169	2.813	1356.431	4.018	337.589	42
2456	**14.608**	**77.896**	**3.219**	**1263.714**	**4.195**	**301.651**	**40**

Table 8 Average physical and mechanical properties of the specimens prepared with gyratory and Marshall compactors (Gyratory compactor specimens were prepared utilising 61.5 mm as the specimen height)

	Unit weight (kg/m^3)	VMA (%)	V_f (%)	V_a (%)	Stability (kg)	Flow (mm)	MQ (kg/mm)	Blows and gyration number
Marshall	2465	14.919	76.990	3.443	1294.355	3.463	376.899	50
Gyratory	2456	14.608	77.896	3.219	1263.714	4.195	301.651	40
% difference	− 0.365	− 2.085	+ 1.177	− 6.506	− 2.367	+ 21.138	− 19.965	–

Table 9 The average physical and mechanical test values of gyratory compactor specimens prepared by 600 kPa vertical stress and gyration angles varying from 1.25° to 1.85°

Gyration angle	Unit weight (kg/m^3)	Voids in mineral aggregate (%)	Voids filled with asphalt (%)	Air voids (%)	Stability (kg)	Flow (mm)	Marshall quotient (kg/mm)	Specimen height (mm)
1.25°	2451	14.763	76.936	3.395	1261.565	4.059	311.174	61.32
1.30°	2443	15.040	75.265	3.709	1262.811	4.503	280.695	61.73
1.35°	2443	15.043	75.239	3.713	1238.007	4.439	279.448	61.56
1.40°	2447	14.908	76.042	3.559	1271.629	4.222	301.121	61.63
1.45°	2442	15.096	74.932	3.772	1202.517	4.303	279.276	61.68
1.50°	2450	14.824	76.557	3.465	1245.729	3.993	314.446	61.66
1.55°	2445	14.971	75.673	3.631	1273.325	4.443	286.523	61.91
1.60°	2459	14.485	78.675	3.080	1255.555	4.167	301.537	61.35
1.65°	2457	14.581	78.074	3.189	1257.673	4.214	298.338	61.49
1.70°	2462	14.383	79.316	2.965	1328.866	4.363	304.695	61.31
1.75°	2459	14.510	78.493	3.108	1334.513	4.336	307.985	61.22
1.80°	2460	14.469	78.758	3.062	1341.687	4.300	312.526	61.34
1.85°	2464	14.329	79.662	2.903	1327.703	4.086	333.426	61.10

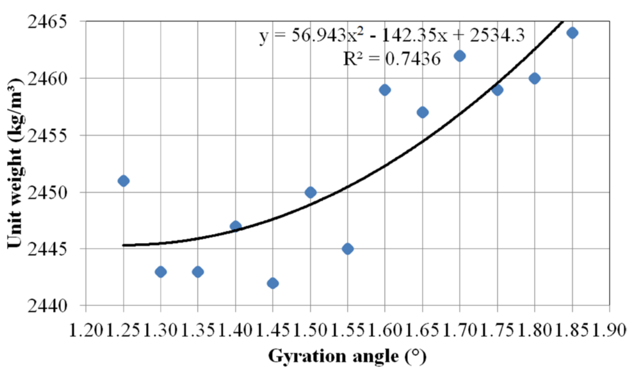

Fig. 10 Unit weight versus gyration angle for 600 kPa ram pressure analyses

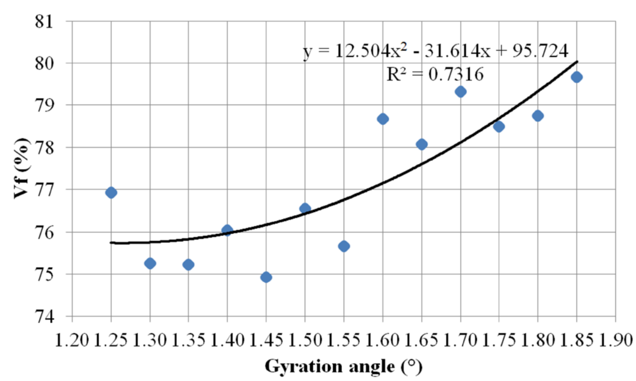

Fig. 12 Voids filled with asphalt versus gyration angle for 600 kPa ram pressure analyses

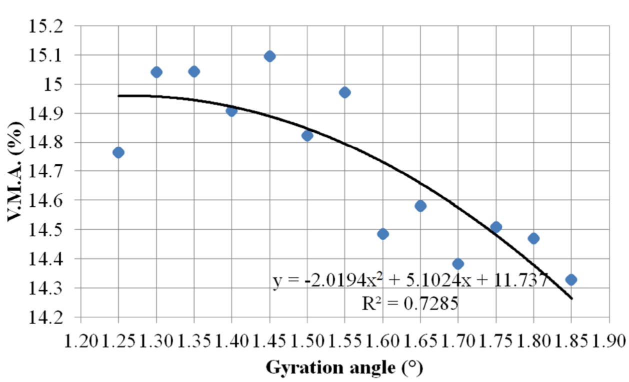

Fig. 11 Voids in mineral aggregate versus gyration angle for 600 kPa ram pressure analyses

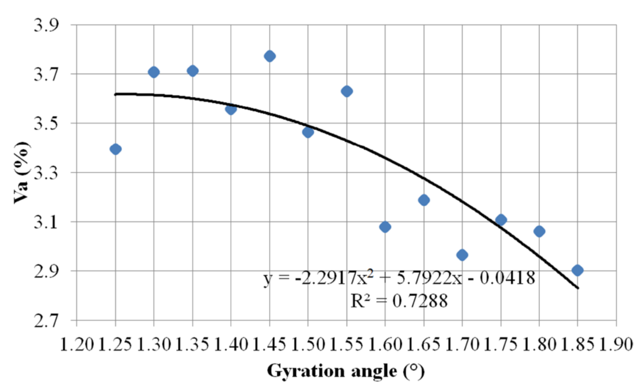

Fig. 13 (Air voids) versus gyration angle for 600 kPa ram pressure analyses

gyration number are 600 kPa ram pressure, 1.25° gyration angle, a gyration speed of 30 rpm and at least 145 °C of compaction temperature. The coefficient of determination for all of the parameters analysed are well above 0.95,

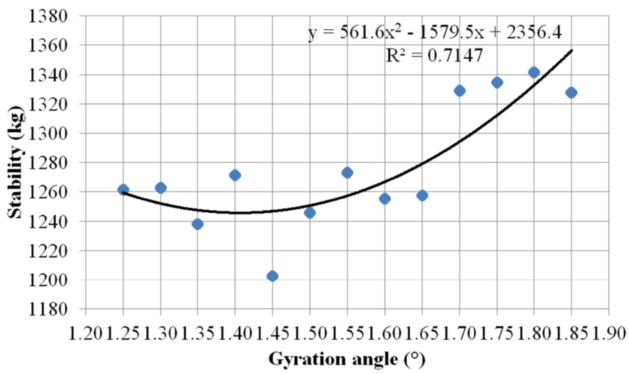

Fig. 14 Stability versus gyration angle for 600 kPa ram pressure analyses

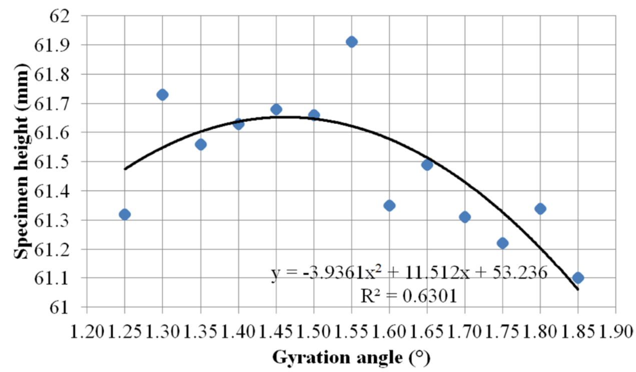

Fig. 17 Specimen height versus gyration angle for 600 kPa ram pressure analyses

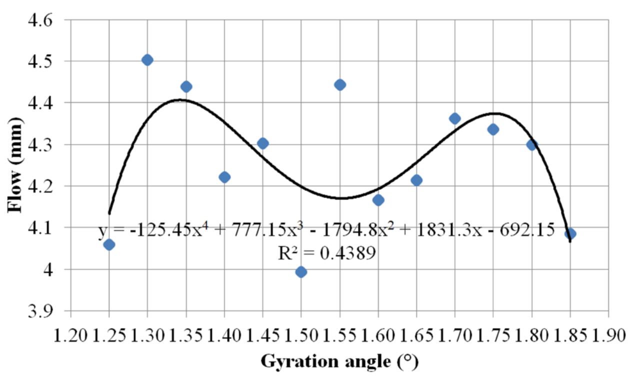

Fig. 15 Flow versus gyration angle for 600 kPa ram pressure analyses

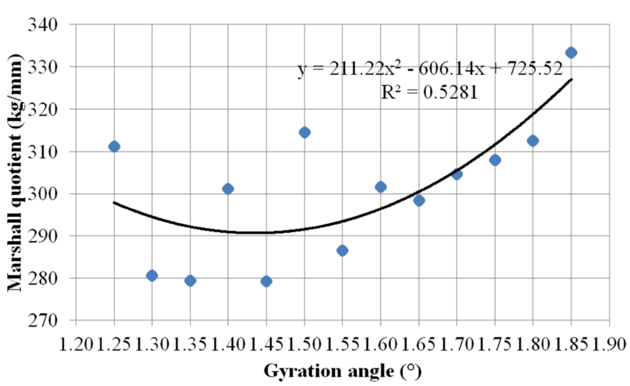

Fig. 16 Marshall quotient versus gyration angle for 600 kPa ram pressure analyses

except specimen height (which is 0.92). Therefore, it can be concluded that the 100 mm-diameter specimens were prepared in a reliable manner. The stability values are well above 900 kg, see Fig. 6. Therefore, there is no problem about the maximum amount of load the specimen can carry before failure. At gyration numbers below 40 as highlighted in Fig. 5, the air void values are between 3.395 and 3.790%. Standards dictate that air void values should be between 3 and 5% for an acceptable surface course mixture [7]. The obtained air void values fall well within the limits of the acting standards. Values for voids filled with asphalt should be between 65 and 75% according to the acting standards. In Fig. 5, for 40 gyrations, the value of the voids filled with asphalt is 76.396% which is above the limit. This is a fairly predictable difference when the very different compaction pattern in gyratory compactors is considered. The values of voids in mineral aggregate are well above 14% for the gyration number values less than 40 so the limits of the standards are attained (refer to Fig. 3). According to the General Directorate of Highways, the flow values should lie between 2 and 4 mm for Marshall specimens but as the gyratory compaction technique is completely different from the previous one, the value of 4.059 mm is understandable and acceptable for 40 gyrations. To be able to arrive at more solid conclusions, and because of the nature of gyratory compaction, more specimens with 61.5 mm specimen height were prepared and tested mechanically further [8]. Figure 9 shows the correspondence of 61.5 mm height to a gyration number of 40 being analogous with the previous results. Another series of specimens was prepared and mechanically tested to ensure the design gyration number. When Tables 6, 7 and 8 are analysed, it can be visualised that the 40 gyration number can be accepted as the design gyration number for 100 mm-diameter gyratory compactor specimens. The difference in flow, and therefore Marshall Quotient values, is self-explanatory as gyratory compaction is a totally a different and much better way of simulating the actual compaction processes on site. So, it can be concluded that flow values, by themselves, do not give an actual and completely correct determination of deformation of the specimen before failure.

To further clarify the testing pattern, another series of tests was performed by changing the gyration angle from 1.25° to 1.85° by 0.05° increments with gyration number

Table 10 The average physical and mechanical test values of gyratory compactor specimens prepared by 240 kPa vertical stress and 2.00° gyration angle analyses with varying gyration number

Gyration number	Unit weight (kg/m^3)	Voids in mineral aggregate (%)	Voids filled with asphalt (%)	Air voids (%)	Stability (kg)	Flow (mm)	Marshall quotient (kg/mm)	Specimen height (mm)
30	2409	16.250	68.664	5.081	909.790	5.020	181.365	63.36
40	2434	15.378	73.314	4.092	1108.656	5.051	219.759	62.45
50	2450	14.828	76.526	3.468	1175.299	4.854	242.548	61.97
60	2463	14.347	79.539	2.923	1029.143	4.809	212.140	61.40
70	2465	14.306	79.814	2.877	1273.392	4.651	275.421	61.41
80	2473	14.012	81.802	2.544	1341.567	4.694	285.749	60.96

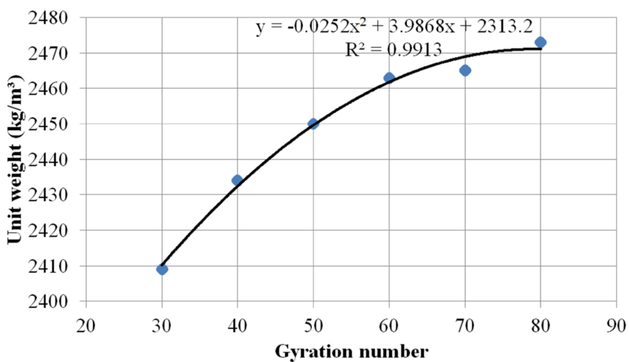

Fig. 18 Unit weight versus gyration number for 240 kPa ram pressure and 2° gyration angle analyses

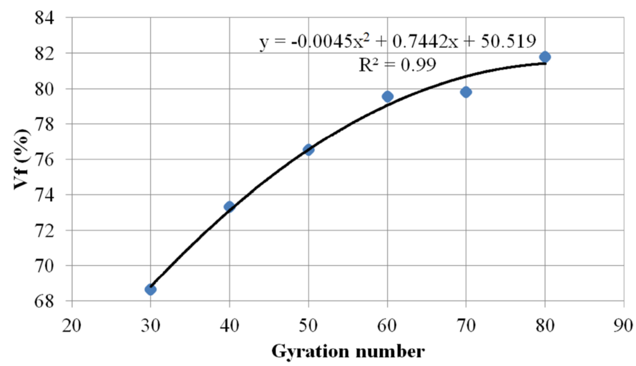

Fig. 20 Voids filled with asphalt versus gyration number for 240 kPa ram pressure and 2° gyration angle analyses

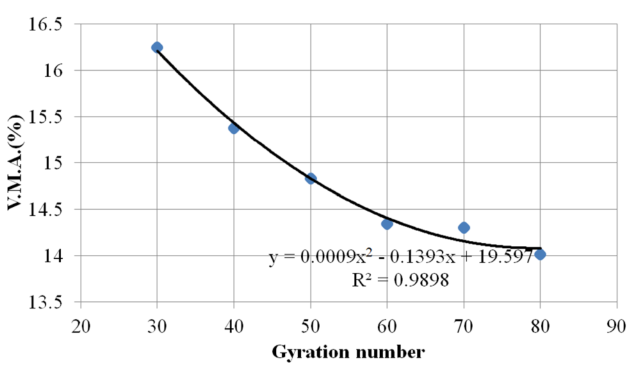

Fig. 19 Voids in mineral aggregate versus gyration number for 240 kPa ram pressure and 2° gyration angle analyses

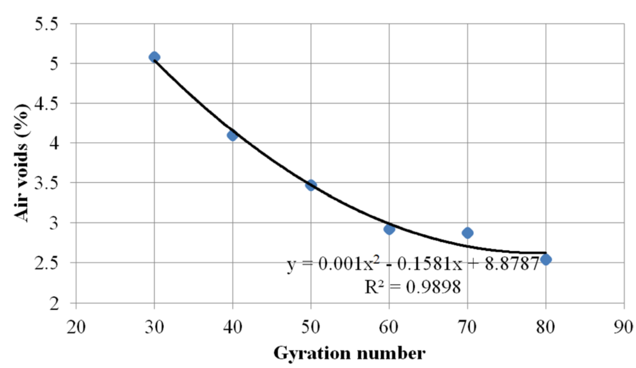

Fig. 21 (Air voids) versus gyration number for 240 kPa ram pressure and 2° gyration angle analyses

value of 40. This series of experiments provides a sound basis for the effect of changing the parameter of the angle of gyration. To further check whether changing the gyration angle to values other than 1.25° makes any significant difference, one-way anova analyses were carried out. When the averages of the test results were compared, no changes were seen between 1.25° and the other angles' test results. This shows the statistical significance of 1.25° as the standard gyration angle value in the gyratory compaction technique. However, there are statistically significant differences between some of the other two by two comparisons which could be a topic for further research.

Additionally, a completely different pattern of loading was also utilised; 240 kPa, 2° gyration angle, a gyration speed of 30 rpm and a minimum compaction temperature of 145 °C. As can be seen from Table 10 and Figs. 18, 19, 20, 21, 22, 23, 24 and 25, when the gyration number increases, as can be expected, the 100 mm gyratory compactor specimens become more densely compacted. As the level of applied stress is much lower than 600 kPa, it is evident that

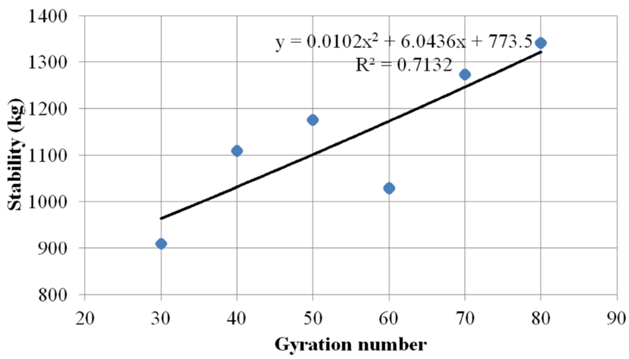

Fig. 22 Stability versus gyration number for 240 kPa ram pressure and 2° gyration angle analyses

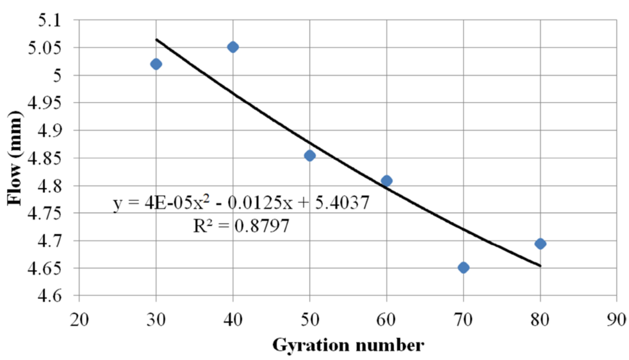

Fig. 23 Flow versus gyration number for 240 kPa ram pressure and 2° gyration angle analyses

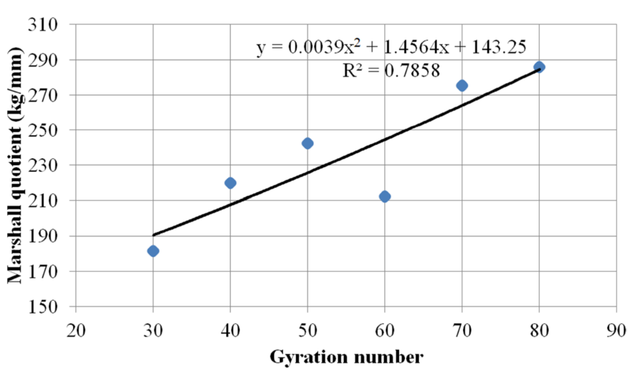

Fig. 24 Marshall quotient versus gyration number for 240 kPa ram pressure and 2° gyration angle analyses

the number of gyrations will be higher to achieve a similar degree of compaction. When Table 11 is examined, it can be seen that 50 gyrations of 240 kPa–2° pattern (with a gyration speed of 30 rpm and at least 145 °C of compaction temperature) is producing similar specimens to the 600 kPa–1.25° pattern. The amount of compactive effort is 25% higher in the low level of stress application and produces very similar specimens. Unit weight values of the two patterns are

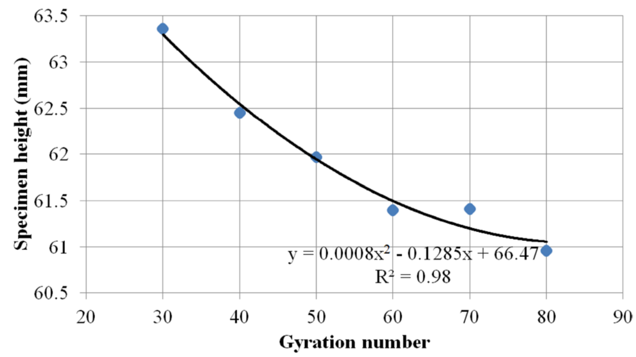

Fig. 25 Specimen height versus gyration number for 240 kPa ram pressure and 2° gyration angle analyses

approximately the same. Voids in mineral aggregate, voids filled with asphalt and air voids values are again very similar. So, it can be clearly seen that physically, the two sets of specimens have approximately the same quantities. Marshall stability values also correlate in the two different testing protocols in an acceptable manner, but flow values do not. There is approximately a 25% increase in the 240 kPa–2° pattern which deserves attention. Therefore, it can be concluded from the data set that when the amount of compactive effort increases, the flow values decrease with the gyration number.

With 50 as the design gyration number obtained from these studies, another set of specimens was tested where the gyration angle was changed from 1.60° to 2.40° (in increments of 0.20°). From these experiments, it was concluded that it was possible to prepare 100 mm-diameter gyratory compactor specimens in a laboratory environment conforming to current standards. When the above Figs. 26, 27, 28, 29, 30, 31, 32 and 33 are examined, it can be seen that when the gyration angle decreases in the same gyration number pattern, the 100 mm gyratory compactor specimens become more densely compacted and therefore the air void values reduce, the unit weight values increase, voids filled with asphalt values increase, stability values also increase by a small amount (as the number of gyrations is the main parameter affecting the stability value) and specimen heights decrease. Again, as in the previous discussions, it is not possible to come to any solid conclusions about the flow and Marshall Quotient values which can be clearly seen in Figs. 31 and 32. This series of experiments provides a sound basis for the effect of changing the parameter of the angle of gyration which in fact is responsible for the further compaction.

The study further tackles the problem of preparing 100 mm-diameter gyratory compactor specimens and shows their superior properties compared to the Marshall specimens, especially in terms of being lighter, having more air voids and very similar Marshall stability values. They also

Table 11 Average physical and mechanical properties of the specimens prepared with two different compaction techniques

Gyration pattern	Unit weight (kg/m^3)	Voids in mineral aggregate (%)	Voids filled with asphalt (%)	Air voids (%)	Stability (kg)	Flow (mm)	Marshall quotient (kg/mm)	Specimen height (mm)
50 gyration, 240 kPa	2450	14.828	76.526	3.468	1175.299	4.854	242.548	61.97
40 gyration, 600 kPa	2451	14.763	76.936	3.395	1261.565	4.059	311.174	61.32

Table 12 The average physical and mechanical test values of gyratory compactor specimens prepared with 240 kPa vertical stress and gyration angles varying from 2.40° to 1.60°

Gyration angle	Unit weight (kg/m^3)	Voids in mineral aggregate (%)	Voids filled with asphalt (%)	Air voids (%)	Stability (kg)	Flow (mm)	Marshall quotient (kg/mm)	Specimen height (mm)
2.40°	2453	14.728	77.152	3.356	1172.507	4.773	246.205	61.75
2.20°	2450	14.828	76.526	3.468	1175.299	4.854	242.548	61.97
2.00°	2453	14.714	77.218	3.340	1209.365	4.788	253.814	61.81
1.80°	2435	15.330	73.591	4.037	1152.817	4.800	240.191	62.13
1.60°	2425	15.674	71.675	4.427	1101.813	4.884	225.843	62.32

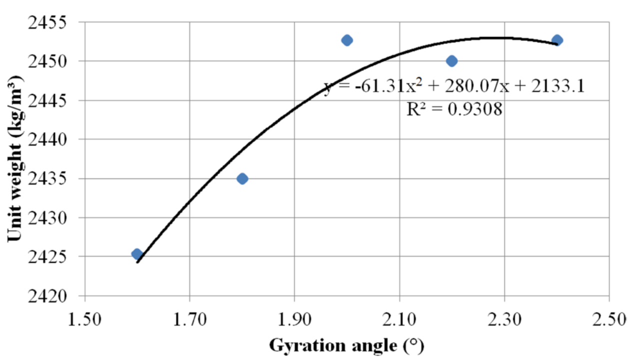

Fig. 26 Unit weight versus gyration angle for 240 kPa ram pressure analyses

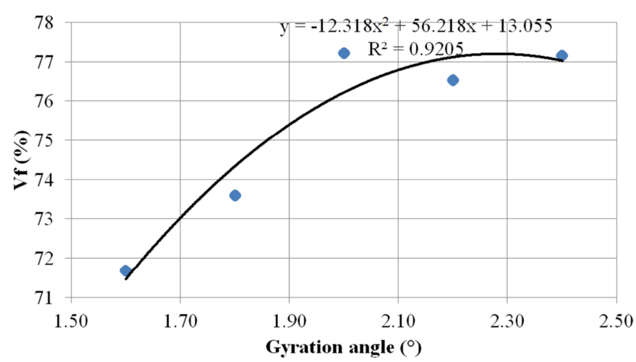

Fig. 28 Voids filled with asphalt versus gyration angle for 240 kPa ram pressure analyses

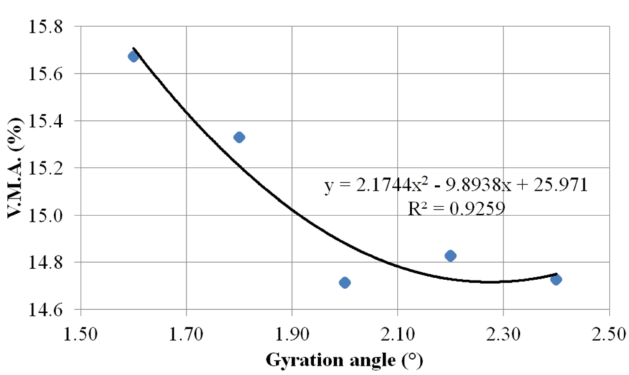

Fig. 27 Voids in mineral aggregate versus gyration angle for 240 kPa ram pressure analyses

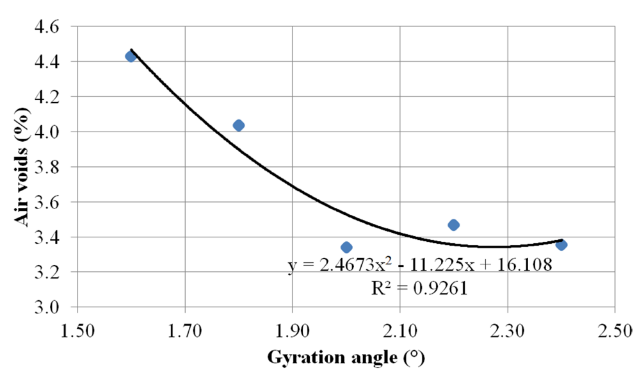

Fig. 29 Air voids versus gyration angle for 240 kPa ram pressure analyses

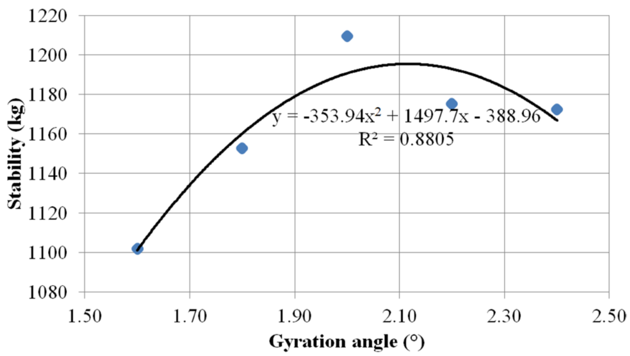

Fig. 30 Stability versus gyration angle for 240 kPa ram pressure analyses

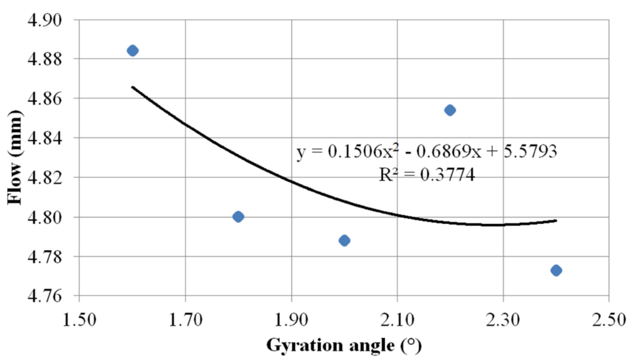

Fig. 31 Flow versus gyration angle for 240 kPa ram pressure analyses

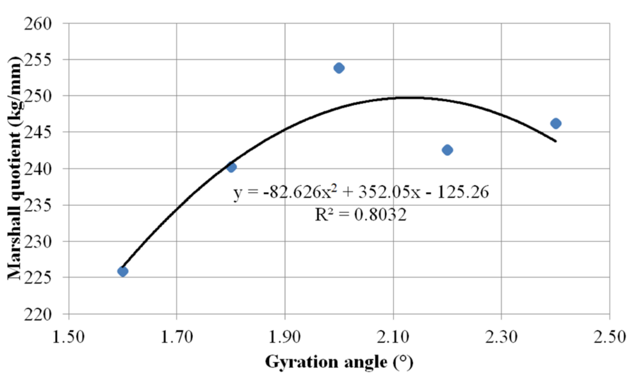

Fig. 32 Marshall quotient versus gyration angle for 240 kPa ram pressure analyses

serve as a much better method of simulation of compaction on site (one has to bear in mind that the flow values of gyratory compactor specimens are higher than Marshall specimens because of the completely different compaction pattern). These gyratory compactor specimens can be modified with polymer modifiers to visualise the effect of modification. New design gyration numbers can then be obtained from these new samples. Also, the rutting susceptibility of these mixtures can be studied with universal testing systems

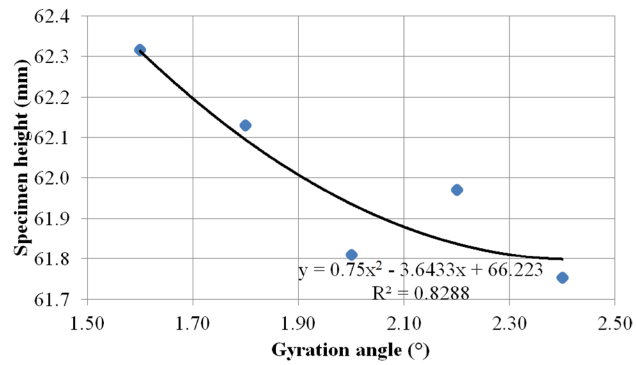

Fig. 33 Specimen height versus gyration angle for 240 kPa ram pressure analyses

for both reference and polymer modified 100 mm gyratory compactor specimens.

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